Depositional Environments of the Pictured Cliffs Sandstone, Late Cretaceous, near Durango, Colorado[1]

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ABSTRACT. The Pictured Cliffs Sandstone was deposited in the northwestern part of the San Juan Basin (Colorado-New Mexico) during the last regression of the Cretaceous Interior Seaway. The unit is generally interpreted as deltaic or marginal marine; however, outcrops near Durango, CO, consist of repetitive sequences of hummocky stratified (HS) sandstone. Each HS sequence consists of a scoured surface overlain by hummocky-stratified, fine-grained sandstone 20-50 cm thick, overlain by ripple- to planar-laminated, bioturbated, very fine-grained sandstone to mudstone. Amalgamated HS sequences are as much as 7 m thick.

Hummocky stratification is an important sedimentary structure indicating storm deposits (tempestites) in the geological record. Rocks containing HS have been found throughout the world, including Ohio. The goal of this research was to apply field and laboratory methods to the re-interpretation of the Pictured Cliffs Sandstone in recognition of the significance of HS.

In this region, the Pictured Cliffs Sandstone was deposited on a storm-dominated, sandy shelf at depths between fair-weather and storm-weather wavebase (about 10 m). Individual storm events are represented by a single HS sequence. Some HS sequences are amalgamated because of either bioturbation or erosion of the upper part of the sequence by subsequent storm events. The thick sand bodies suggest that significant amounts of sediment were transported along the shelf during progradation of the shoreline. During storm events these sediments were resuspended and re-deposited, creating the HS sequences.

OHIO J. SCI. 93 (4): 83–89, 1993

INTRODUCTION

Sandy shelf deposits are excellent sedimentary units to study because they contain lithofacies which are usually very well preserved and easy to identify. Lithofacies are individual rock units that are described based on their composition, texture, and internal sedimentary structures. Each lithofacies is representative of a characteristic depositional event; therefore, a large amount of information about the depositional history of the sedimentary rocks can be gathered through field and laboratory studies. This information can be used to interpret the depositional environment where the sedimentary rocks were formed.

The San Juan Basin is a large structural basin located in the eastern part of the Colorado Plateau (Fig. 1) and contains a thick sequence of Cretaceous and Tertiary rocks which crop out in a large region of northwestern New Mexico and southwestern Colorado (Blatz 1967). The Late Cretaceous Pictured Cliffs Sandstone was deposited in this basin along the ancient epicontinental shelf within the Late Cretaceous Interior Seaway. The Pictured Cliffs Sandstone is recognized as the last regressive sand body that was deposited during a series of transgressive-regressive events (Sears et al. 1941).

The Pictured Cliffs Sandstone was named and first described by Holmes (1877). Reeside (1924) divided the unit into a lower part that contains alternating beds of a grey sandy shale and massive yellow to brown sandstone units, and an upper part that contains massive beds of white to brown, fine-grained sandstone. Fassett and Hinds

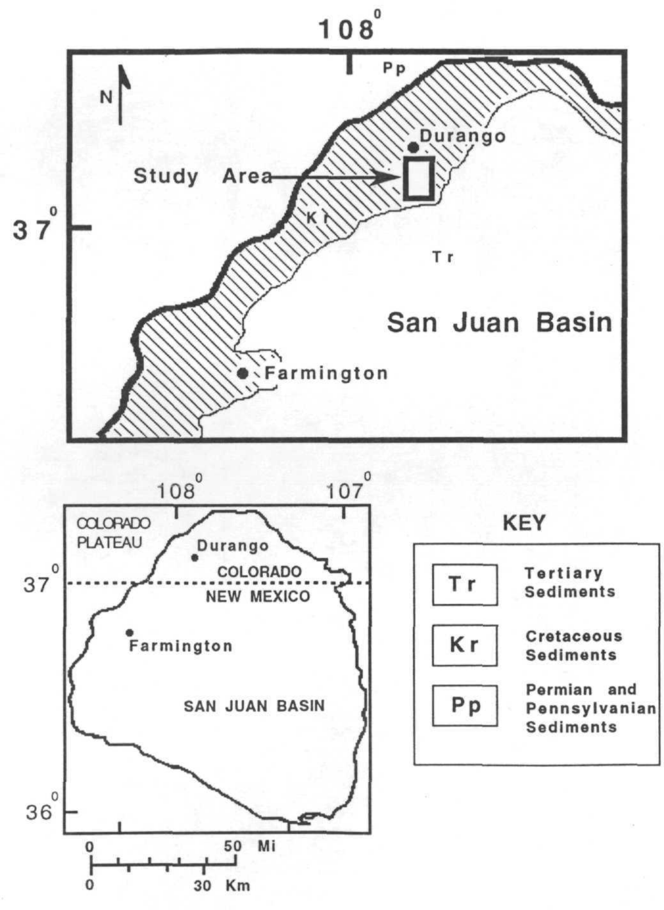

FIGURE 1. Location map showing the extent of the San Juan Basin in western Colorado and New Mexico along with the age of exposed rocks and the study area.

[1]Manuscript received 8 March 1993 and in revised form 19 July 1993 (#93-10).

(1971) interpreted the Pictured Cliffs Sandstone to represent shallow-marine and beach depositional environments, but did not include descriptions of individual lithofacies. More recent studies have focused on describing the lithofacies types of the Pictured Cliffs Sandstone and related rocks in the southwestern part of the San Juan Basin (Donselaar 1989, Flores and Erpenbeck 1981, Fassett 1975). Studies of the Pictured Cliffs Sandstone in the northwest part of the basin have only considered sandstone petrology (Aubrey 1991, Molenaar and Baird 1991).

The present research focuses on a large outcrop of the Pictured Cliffs Sandstone exposed along State Road 160, in the northwest part of the San Juan Basin, south of Durango, CO. Here the Pictured Cliffs Sandstone overlies the Lewis Shale and is the last vertical exposed unit in this section (elsewhere in the basin, the Pictured Cliffs is overlain by the Fruitland Formation). Field and laboratory studies permit the recognition of individual lithofacies types within this sandstone sequence giving clues as to the interpretation of the depositional environment.

The present study was initiated after recognizing hummocky stratification (HS) sequences in the Pictured Cliffs Sandstone in the northwest part of the San Juan Basin. Studies on HS within the last few decades have shown it to be diagnostic of deposition on clastic and carbonate shelves between fair-weather and storm-weather wavebase (Cotter 1990, Duke et al. 1991, Southard et al. 1990, Craft and Bridge 1987, Handford 1986, Duke 1985, Bourgeois

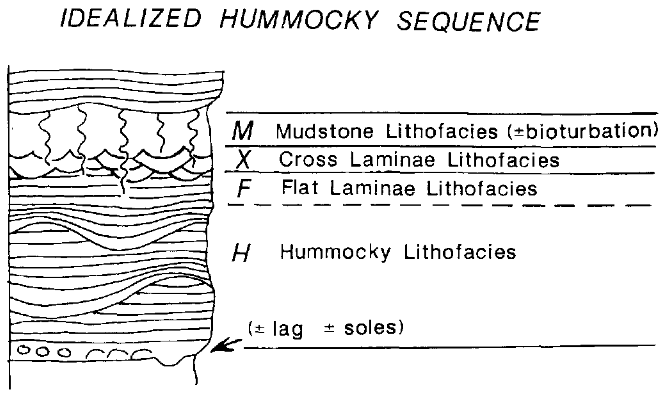

FIGURE 2. A proposed idealized hummocky stratification sequence, showing the erosional base, hummocky stratified lithofacies, overlain by a massive-to-stratified lithofacies, overlain by the cross-laminated lithofacies, overlain by the laminated to massive and bioturbated siltstone to mudstone lithofacies (modified from Dott and Bourgeois 1982).

1980). Geographically, HS is not confined to one particular region. HS has been recognized in outcrops of the Berea Sandstone near Columbus, OH (Coats 1988), and can be found in outcrops of ancient shelf depositional systems throughout the world, which makes it valuable in the interpretation of paleoenvironments.

Dott and Bourgeois (1982) proposed an idealized sequence for HS (Fig. 2). This idealized sequence is rarely observed in nature. However, variations of the sequence

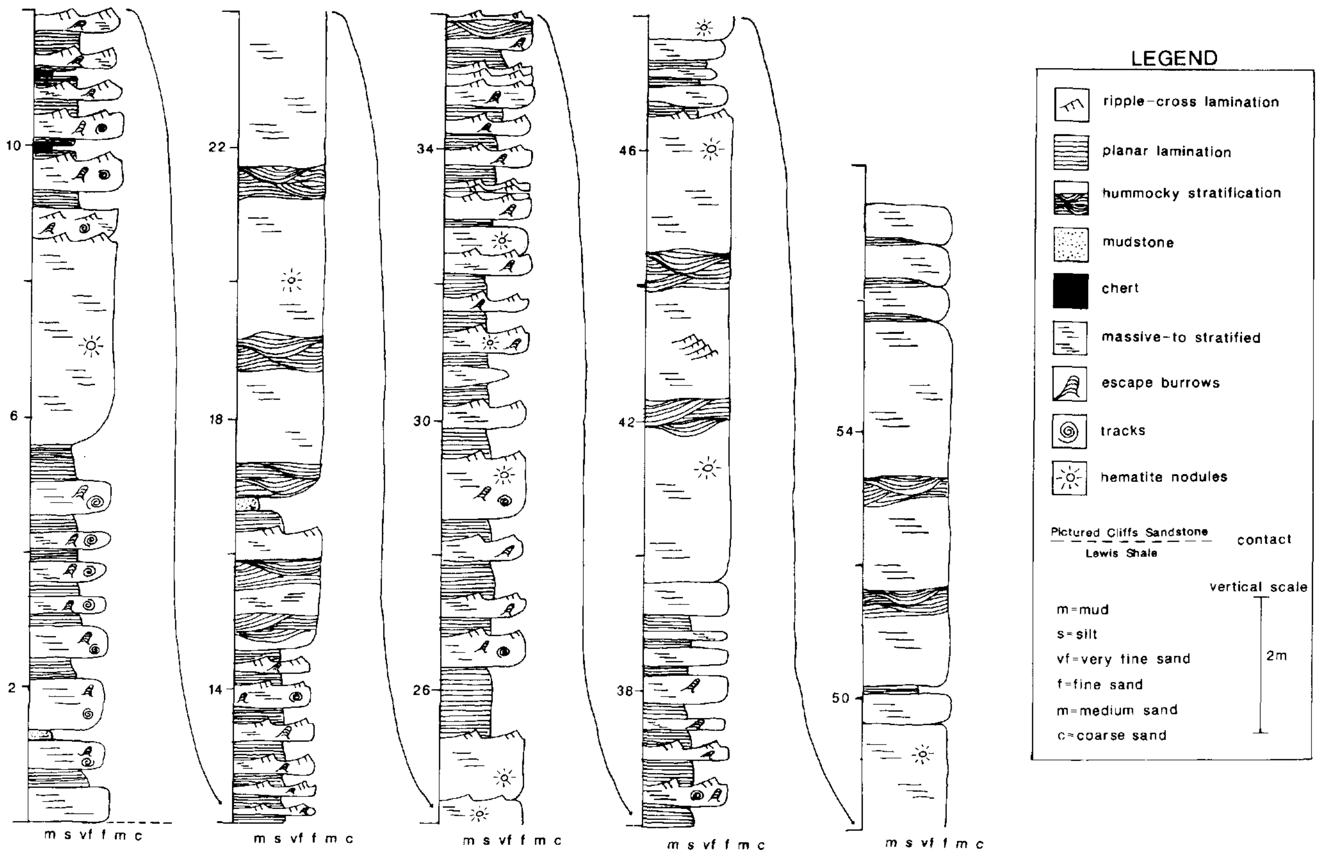

FIGURE 3. Stratigraphic section of the Pictured Cliffs Sandstone in the study area. The contact between the Lewis Shale and the Pictured Cliffs Sandstone was placed at the base of the first sandstone bed >0.5 m thick (lower left column). Vertical scale gives thickness, horizontal scale gives grain size (see key for symbols).

are common and easily recognized. The goals of the present study were to: document the presence of HS in the Pictured Cliffs Sandstone, examine variations in HS sequences and their implications for depositional environment, and interpret the depositional setting of the Pictured Cliffs Sandstone.

MATERIALS AND METHODS

A stratigraphic section was constructed from an outcrop located on S.R. 160, south of Durango, CO (map coordinates T.34N., R.9W., SEC 9, NE 1/4, SW 1/4 of the Loma Linda, Colorado 7.5 minute quadrangle map). The Pictured Cliffs Sandstone was measured from the gradational basal contact with the Late Cretaceous Lewis Shale (Fig. 3). Fourteen rock samples were collected for sandstone petrography. Five thin sections were point counted for modal analysis (300 grains per thin section) using the Gazzi-Dickinson method (Ingersoll et al. 1984), and the results were plotted on a tertiary diagram. Four lithofacies were described in the field and used in a Markov Chain analyses with the computer program BMDP-4F (Brown 1983) in order to recognize a predictable stratigraphic order within the section. This type of analysis provides insight to the hydrodynamics and paleodepositional events of this ancient environment. From this method a variation of the idealized HS sequence was constructed.

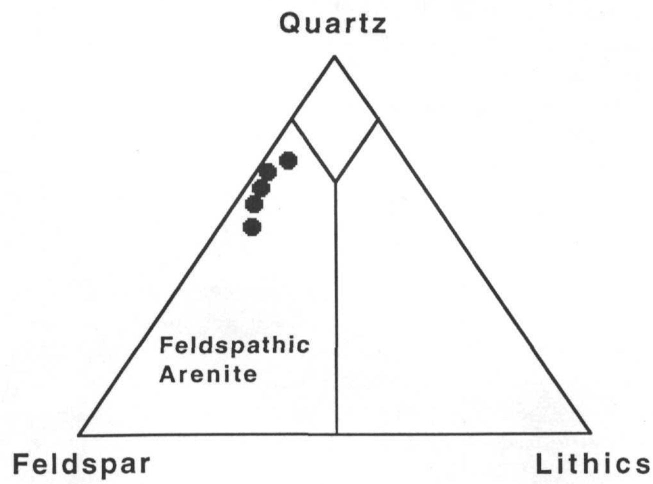

FIGURE 4. Tertiary diagram showing sandstone petrography results. All samples plot in the feldspathic arenite field (modified from Dott 1964).

RESULTS

Pictured Cliffs Sandstone

The sandstone petrography results were plotted on a QFL diagram (Fig. 4). All five thin sections plot in the feldspathic arenite field. From the field and laboratory studies, it was concluded that the Pictured Cliffs Sandstone contains alternating beds of a grey argillaceous siltstone

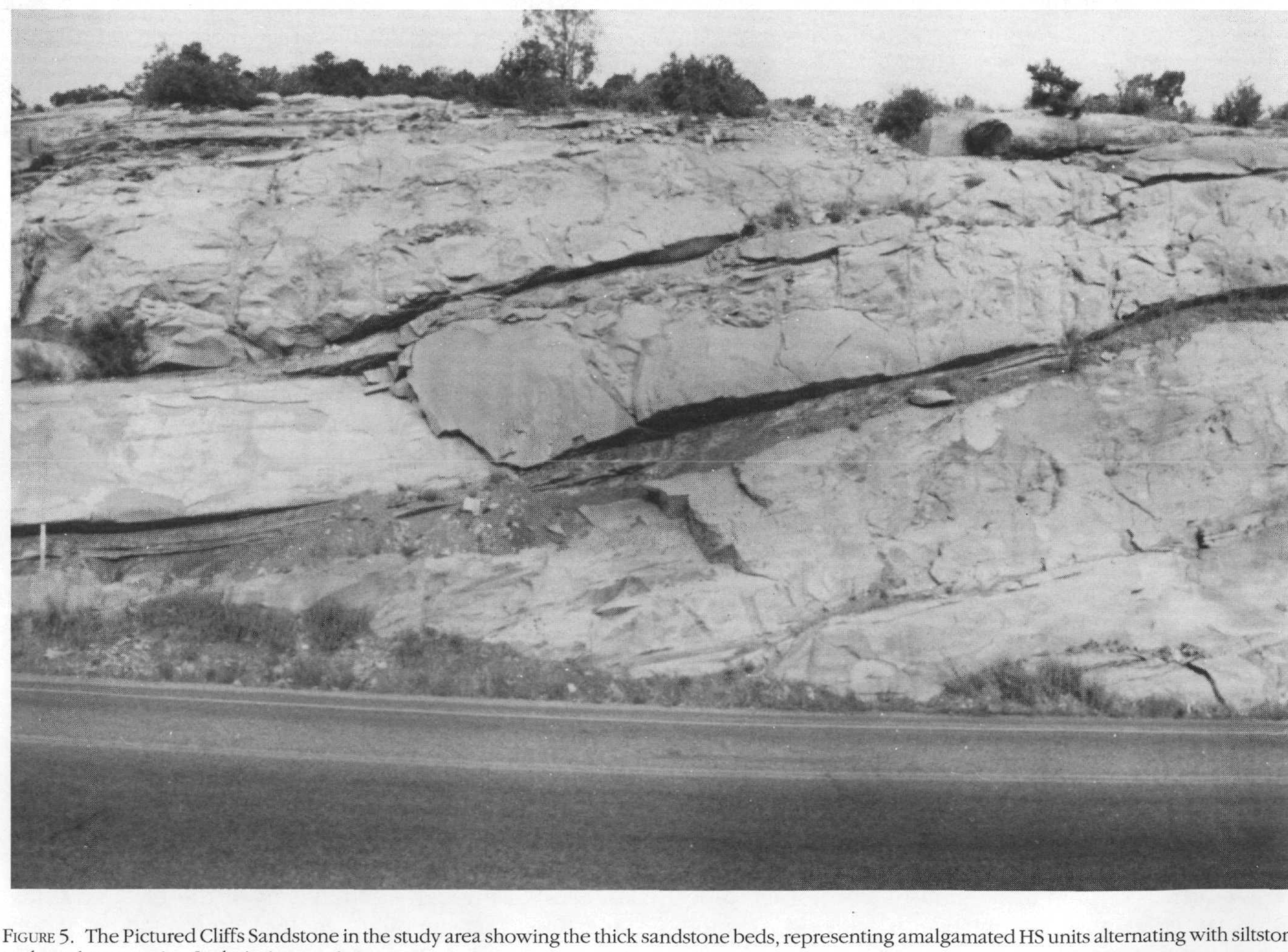

FIGURE 5. The Pictured Cliffs Sandstone in the study area showing the thick sandstone beds, representing amalgamated HS units alternating with siltstone and mudstone units. Scale is 1 cm = 1 m.

and fine-grained, well-sorted, calcareous grey feldspathic arenite which weathers to a light tan color (Fig. 5). This lithologic description of the Pictured Cliffs Sandstone is consistent with previous studies.

A 58 m section was measured through the upper part of the Lewis Shale, and entire Pictured Cliffs Sandstone (Fig. 3). The basal contact of the Pictured Cliffs Sandstone is intercalated with the Lewis Shale. Therefore, measurement of the section began at the bottom of the first sandstone bed with a thickness greater than 50 cm. Upward, the sandstone beds become thicker and the siltstone beds thinner. Six lithofacies types were identified within the measured section. The lithofacies types include hummocky stratified sandstone (lithofacies H), massive-to-stratified sandstone (lithofacies Ss), ripple-laminated sandstone (lithofacies X), planar-laminated siltstone to mudstone (lithofacies Ls), massive mudstone (lithofacies M), and bedded chert (lithofacies C).

FIGURE 7. The bottom of an H type sandstone bed displaying the trace fossil *Thalassinoides*. The burrow in the middle of the photograph is approximately 45 cm long measured from the right (where it bifricates from the main trunk) to the left.

Lithofacies Descriptions

Lithofacies H was described as a fine-grained, well-sorted, calcareous feldspathic arenite with hummocky stratification (HS). Individual hummocky units were 0.3 to 1 m thick, and some were amalgamated. This lithofacies shows evidence of staining from micro-concretions of hematite. Some of the HS sequences contained hematite staining within the laminations, making the sedimentary structures easier to recognize (Fig. 6). Trace fossils were abundant at the basal contact of the lithofacies. Sandstones in this lithofacies commonly contained *Thalassinoides* and *Ophiomorpha* ichnogenera (Fig. 7).

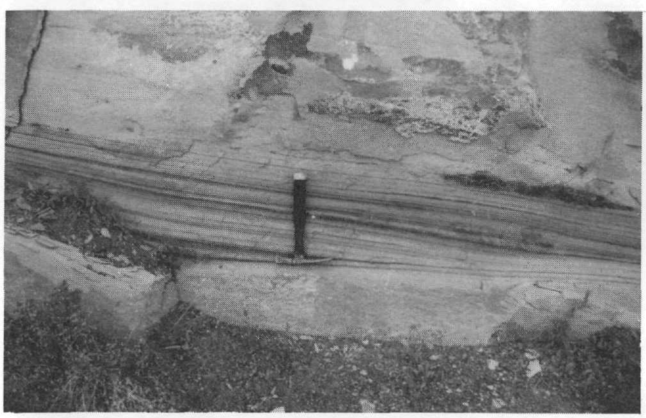

FIGURE 6. The base of a hummocky stratified sandstone unit (lithofacies H), showing low angle truncations at the hummock margins. Note the hematite staining which highlights the hummocky stratification within the sandstone. The overlying, massive-to-stratified sandstone is probably also hummocky-stratified, but weathers indistinctly.

Lithofacies Ss closely resembled lithofacies H in composition and texture, but did not reveal hummocky stratification. The unit is massive to indistinctly stratified. We believe that this unit is hummocky stratified throughout, based upon its close association with lithofacies HS. Recognizable HS within these sandstones appears to be related to secondary weathering of iron oxides to accentuate laminae. Lithofacies Ss is probably not de-stratified, given the lack of fluid escape structures and the low abundance of burrows.

Lithofacies X was described as a very fine-grained, well-sorted, calcareous quartz arenite with ripple lamination and climbing-ripple lamination sets up to 1 m thick that terminated in symmetrical ripple marks at the tops of beds. The laminations were commonly separated by lenticules of hematite, making the ripple sets easy to recognize.

Lithofacies Ls was a very-fine grained, calcareous grey quartz arenite-to-siltstone and mudstone, with planar lamination. *Thalassinoides* was a common trace fossil in this lithofacies. The individual beds occurred in thicknesses of 0.1 to 0.5 m.

Lithofacies M was a calcareous dark-grey massive mudstone of thicknesses up to 7 cm.

Lithofacies C was described as a dark-red to brown, calcareous bedded chert that was internally massive and convoluted at the base. These beds were rare in the section, and measured individually up to 3 cm thick.

DISCUSSION

Lithofacies Interpretations

Markov Chain analysis was used to recognize a predictable stratigraphic order for the vertical sequence. By using the six lithofacies types in the statistical procedure, a preferred transition of four lithofacies was detected (Fig. 8). This succession of lithofacies is a variation of the idealized HS sequence (Dott and Bourgeois 1982), and consists of bioturbated hummocky stratified sandstone (lithofacies H), overlain by ripple cross-laminated sandstone (lithofacies X), overlain by laminated siltstone to mudstone (lithofacies Ls), overlain by chert (lithofacies C). The double-sided arrow in the lithofacies transition from Ls to C represents the probability that Ls can both underlie and overly C. Statistically, lithofacies Ss and M did not appear in the predicted lithofacies transitions. However, the fact that these two lithofacies were deposited as part of the Pictured Cliffs Sandstone was important in the interpretation of the depositional environment.

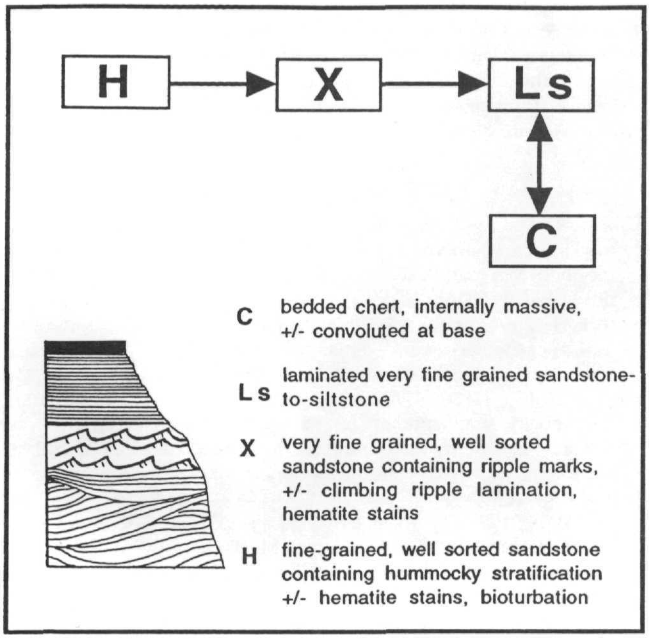

FIGURE 8. Preferred lithofacies transition from a Markov Chain analysis and preferred lithofacies section as it may appear in the outcrop. The preferred lithofacies transitions are from lithofacies H, to lithofacies X, to lithofacies Ls, to lithofacies C and represents a hummocky stratified sequence. The alternation of lithofacies Ls to C represents changes in background sedimentation.

Hummocky stratification was formed as a result of the scouring of the shoreface and inner shelf by large storm waves. As the storm event wanes, the scours are then filled by both the lateral tractive flow of sediment into the scours from wave oscillation and redeposition of sediment out of suspension. The resulting deposit, called a tempestite, consists of a sequence of beds and sedimentary structures with HS being the most significant and diagnostic structure. HS is most commonly preserved below fair-weather wavebase, otherwise the sequence could be destroyed by reworking during fair weather conditions (Dott and Bourgeois 1982). This series of events results in the formation of the HS sequence which was recognized within this section of the Pictured Cliffs Sandstone.

Sequences of HS in the Pictured Cliffs Sandstone formed during storm events when the sediments above storm-weather wavebase were being scoured and eroded. Existing sediment was resuspended and new sediment was being introduced onto the shoreface from storm erosion of the beaches. After each storm event, as the wave action of the nearshore began to wane, the scours were filled by sediment falling from suspension and from the lateral tractive flow of sediment, creating the hummocks in lithofacies H. The wave oscillation ripples of lithofacies X were being deposited over lithofacies H and Ss during the last phase of traction transport associated with the storm event.

Background sedimentation (between storm events) is represented by lithofacies Ls, M, and C. These are equivalent to lithofacies M (a bioturbated mudstone) in the idealized sequence of Dott and Bourgeois (1982). Lithofacies Ls probably represents the fine-grained nearshore sediments associated with the prograding shoreline deposited during fair weather conditions. Lithofacies M is rare in the section and was probably deposited during longer periods of fair weather conditions in which the mud sized particles had sufficient time to settle out of suspension before being reworked. Since lithofacies Ls is the dominant form of background sedimentation, it is considered to be comparable to Lithofacies M of Dott and Bourgeois (1982). Lithofacies C is also rare in this section and represents pelagic sedimentation that may have resulted from seasonal productivity.

The HS sequence predicted by the Markov Chain analysis was found within this section. However, it does not occur repeatedly throughout the section. Amalgamated HS sequences are common in the thicker sandstone beds. These amalgamated sequences are represented by the absence of lithofacies Ls, M, and C in the predicted sequence. Amalgamated HS sequences may have been created by successive storm events that have eroded or removed the upper, fine-grained part of the predicted sequence then redeposited the hummocky stratified sediments on top of existing HS layers. Bioturbation between successive storm events may have also destroyed existing sedimentary structures in some of the HS sequences.

Variations of the idealized HS sequence have been proposed and documented in the stratigraphic record (Cotter 1990, Craft and Bridge 1987, Hunter and Clifton 1982). Amalgamated HS sequences are an example of one type of variation within HS sequences. These variations represent different types of depositional environments and common variations include those in thickness of bedset intervals, thickness of individual hummocky beds, ratio of hummocky stratified sandstone to associated shale, absence of one or more of the lithofacies in the idealized HS sequence, and degree of bioturbation of the hummocky bed sets (Dott and Bourgeois 1982). It is apparent from this section of the Pictured Cliffs Sandstone that the variations of HS sequences can be used to interpret this specific depositional environment.

Depositional Interpretations

In the northwestern part of the San Juan Basin, the Pictured Cliffs Sandstone is representative of a storm-dominated, sandy, middle- to inner-shelf sedimentary sequence. The occurrence of the thick sand bodies is evidence of a large volume of clastic deposition onto the shelf. These prograding sand bodies were most likely being deposited as a result of the basin subsiding during the last regression of the Late Cretaceous (Sears et al. 1941) and by sediment influx from deltaic environments which have been interpreted to exist elsewhere in the depositional environment (Flores and Erpenbeck 1981).

Sediment sources were most likely the adjacent deltaic environments through which sediments were introduced onto the shelf, then transported and deposited along the shoreline areas by the longshore currents. Depositional rates probably increased during storm events when larger storm waves resuspended the sediment below fair-weather wavebase, while at the same time, storm waves reached the back beach areas and carried more sediment onto the shoreface and middle- to inner-shelf areas. All of these sediments would be deposited from bedload and suspended load offshore to form HS sequences. The large number of escape burrows within lithofacies H also suggest that deposition rates were more rapid during the formation of the HS lithofacies than during normal fair-weather deposition (Simpson 1975).

Previous studies have estimated that the depth of water in which HS sequences are formed can be between 5 m and 30 m (Harms 1979), to a maximum of 60 m (Bourgeois 1980). Probable depth at which HS sequences were formed can be estimated by the type of variated HS sequences that occur within a stratigraphic section. From the variations of HS sequences that occur in the Pictured Cliffs Sandstone, deposition was probably proximal to the shoreline at an estimated depth of 5 m to 15 m. This approximation is based on: 1) the occurrence of the amalgamated HS sequences which are characteristic of inner shelf, shallow storm deposits (Dott and Bourgeois 1982); 2) the presence of lithofacies X and Ls, which suggests that the deposition was taking place on the inner to middle shelf (Brenchley 1985); and 3) the large amount of sandy sediment, which suggests a closer proximity to the shore (Duke 1985).

CONCLUSION

Hummocky-stratified (HS) sequences are present in the Pictured Cliffs Sandstone located in the northwestern San Juan Basin. Statistically, the typical HS sequence consists of: 1) a hummocky-stratified, fine-grained sandstone; 2) overlain by a ripple cross-laminated, very fine-grained sandstone; 3) overlain by a planar-laminated, very fine-grained sandstone-to-siltstone and mudstone; 4) overlain by a thinly-bedded chert.

Within the measured section, the predicted HS sequence is rare because there are only two instances in which the bedded chert is exposed. Therefore, it can be stated that the most common HS sequence within this section of the Pictured Cliffs Sandstone consists of a scoured surface overlain by hummocky-stratified, fine-grained sandstone 20-50 cm thick, overlain by ripple- to planar-laminated, bioturbated, very fine-grained sandstone to mudstone. Amalgamated HS units can be up to 7 m thick in this stratigraphic section.

The HS sequences, along with other environmental indicators such as oscillation ripple marks and escape burrows, suggest that the depositional environment for the Pictured Cliffs Sandstone in this area of the basin was a storm-dominated, inner-shelf environment. The presence of thick sand bodies and the occurrence of amalgamated HS units suggest that deposits were proximal to the shoreline and were created by episodic, large-wave storm events, separated by intervals of fair-weather deposition.

By recognizing this storm-dominated, middle- to inner-shelf sedimentary environment within the northwest part of the San Juan Basin, comparisons can be made to other deposits that formed at the same time in other parts of the basin. The complete description of the sedimentary basin, and how it evolved over time, will eventually permit the development of a basin model that reveals significant geologic events such as tectonism, eustasy, and changes in sediment supply.

ACKNOWLEDGEMENTS. This study was completed as part of an undergraduate thesis project at Bowling Green State University, under the supervision of Dr. James E. Evans. The authors wish to thank Dr. Charles Onasch, Dr. Charles Kahle, Dr. Joseph Mancuso, and Mr. Bill Butcher for their assistance. The authors would also like to thank Andrew Shrock for his assistance in the field.

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